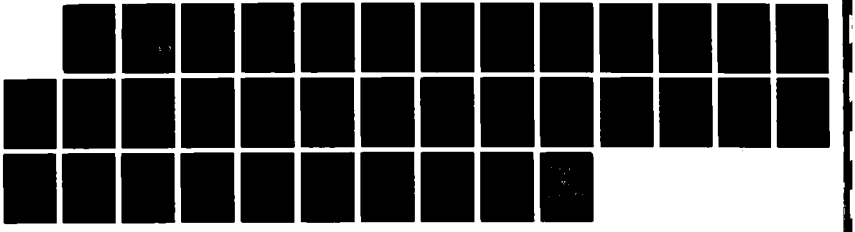
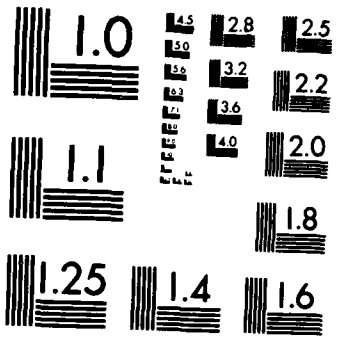
AD-A188 141 NAVAL C3 DISTRIBUTED TACTICAL DECISIONMAKING(U) 1/1
MASSACHUSETTS INST OF TECH CAMBRIDGE LAB FOR
INFORMATION AND DECISION SYSTEMS M ATHANS ET AL.
UNCLASSIFIED 30 OCT 87 LIDS-IR-1712 N00014-85-K-0519 F/G 25/5 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

DTIC FILE COPY

(12)

AD-A188 141

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) NAVAL C^3 DISTRIBUTED TACTICAL DECISIONMAKING		5. TYPE OF REPORT & PERIOD COVERED 1 July 1987-30 September 1987
		6. PERFORMING ORG. REPORT NUMBER LIDS-IR 1712
7. AUTHOR(s) Michael Athans Alexander H.Levis		8. CONTRACT OR GRANT NUMBER(s) N00014-85-K-0519
9. PERFORMING ORGANIZATION NAME AND ADDRESS Laboratory for Information and Decision Systems Massachusetts Institute of Technology Cambridge, Massachusetts 02139		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 649-003
11. CONTROLLING OFFICE NAME AND ADDRESS ENGINEERING PSYCHOLOGY PROGRAMS (CODE 1111) Office of Naval Research Arlington, Virginia 22217-5000		12. REPORT DATE October 30, 1987 13. NUMBER OF PAGES i+34
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Dr. Neil Gerr Mathematical Sciences Division Office of Naval Research Arlington, Virginia 22217-5000		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION. DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DTIC ELECTE NOV 2 3 1987 S D H

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Command and Control, Distributed Decisionmaking, Organization Theory,

Petri Nets.

20. ABST (Continue on reverse side if necessary and identify by block number)

Progress on eight research problems addressing distributed tactical decisionmaking is described.

DD FORM 1473

LABORATORY FOR INFORMATION AND DECISION SYSTEMS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Cambridge, Massachusetts 02139

OSP NUMBER 95442 LIDS-IR-1712

QUARTERLY TECHNICAL REPORT

for the period

1 July 1987 to 30 September 1987

for

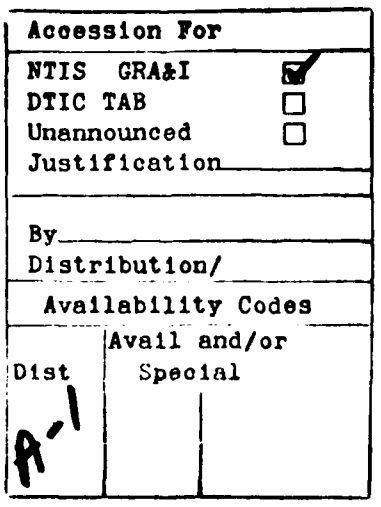
NAVAL C^3 DISTRIBUTED TACTICAL DECISION MAKING

Contract Number N00014-84-K-0519
Work Unit NR 649-003

Submitted to:

Dr. N. Gerr, Code 1111SP
Dr. H. L. Hawkins, Code 1111SP
Dr. R. Madan, Code 414
Dr. W. R. Vaughan, Jr.

Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217-5000



Submitted by:

Michael Athans
Alexander H. Levis

October 28, 1987

NAVAL C^3 DISTRIBUTED TACTICAL DECISIONMAKING

1. PROJECT OBJECTIVES

The objective of the research is to address analytical and computational issues that arise in the modeling, analysis and design of distributed tactical decisionmaking. The research plan has been organized into two highly interrelated research areas:

(a) Distributed Tactical Decision Processes;
(b) Distributed Organization Design.

The focus of the first area is the development of methodologies, models, theories and algorithms directed toward the derivation of superior tactical decision, coordination, and communication strategies of distributed agents in fixed organizational structures. The framework for this research is normative.

The focus of the second area is the development of a quantitative methodology for the evaluation and comparison of alternative organizational structures or architectures. The organizations considered consist of human decisionmakers with bounded rationality who are supported by C^3 systems. The organizations function in a hostile environment where the tempo of operations is fast; consequently, the organizations must be able to respond to events in a timely manner. The framework for this research is descriptive.

2. STATEMENT OF WORK

The research program has been organized into seven technical tasks: four that address primarily the theme of distributed tactical decision processes and three that address the design of distributed organizations. An eighth task addresses the integration of the results. They are:

2.1 Real Time Situation Assessment: Static hypothesis testing, the effect of human constraints and the impact of asynchronous processing on situation assessment tasks will be explored.

2.2 Real Time Resource Allocation: Specific research topics include the use of algebraic structures for distributed decision problems, aggregate solution techniques and coordination.

2.3 Impact of Informational Discrepancy: The effect on distributed decisionmaking of different tactical information being available to different decisionmakers will be explored. The development of an agent model, the modeling of disagreement, and the formulation of coordination strategies to minimize disagreement are specific research issues within this task.

2.4 Constrained Distributed Problem Solving: The agent model will be extended to reflect human decisionmaking limitations such as specialization, limited decision authority, and limited local computational resources. Goal decomposition models will be introduced to derive local agent optimization criteria. This research will be focused on the formulation of optimization problems and their solution.

2.5 Evaluation of Alternative Organizational Architectures: This task will address analytical and computational issues that arise in the construction of the generalized performance-workload locus. This locus is used to describe the performance characteristics of a decisionmaking organization and the workload of individual decisionmakers.

2.6 Asynchronous Protocols: The use of asynchronous protocols in improving the timeliness of the organization's response is the main objective of this task. The tradeoff between timeliness and other performance measures will be investigated.

2.7 Information Support Structures: In this task, the effect of the C^3 system on organizational performance and on the decisionmaker's workload will be studied.

2.8 Integration of Results: A final, eighth task, is included in which the various analytical and computational results will be interpreted in the context of organizational bounded rationality.

3. STATUS REPORT

In the context of the first seven tasks outlined in Section 2, a number of specific research problems have been formulated and are being addressed by graduate research assistants under the supervision of project faculty and staff. Research problems which were completed prior to or were not active during this last quarter have not been included in the report.

3.1 DISTRIBUTED TEAM HYPOTHESIS TESTING WITH EXPENSIVE COMMUNICATIONS

Background: In Command-Control-and-Communication (C^3) systems multiple hypothesis testing problems abound in the surveillance area. Targets must be detected and their attributes must be established; this involves target discrimination and identification. Some target attributes, such as location, are best observed by sensors such as radar. More uncertain target locations are obtained by passive sensors, such as sonar or IR sensors. However, target identity information requires other types of sensors (such as ESM receivers, IR signature analysis, human intelligence etc). As a consequence in order to accurate locate and identify a specific target out of a possibly large potential population (including false targets) one must design a detection and discrimination system which involves the fuzing of information from several different sensors generating possibly specialized information about the target. These sensors may be collocated on a platform (say a ship in a Naval battle group) or be physically dispersed as well (ESM receivers exist in every ship, aircraft, and submarine). The communication of information among this diverse sensor family may be difficult (because of EMCON restrictions) and is vulnerable to enemy countermeasure actions (physical destruction and jamming). It is this class of problems that motivates our research agenda.

To put it another way the fusion of information derived from dispersed sensors and decision nodes requires communication. To discourage nonessential communication we would like to put a price on each transmitted bit. In this manner, extensive communications would occur only if the decision warrants them.

Research Goals: We are conducting research on distributed multiple hypothesis testing using several decision-makers, and teams of decision-makers, *with distinct private information and* limited communications. This is the simplest possible non-trivial distributed decision problem, whose centralized counterpart is well understood and straight-forward to compute. The goal of this research is to *unify* our previous research in situation assessment, distributed hypothesis testing, and impact of informational discrepancy; and to *extend* the methodology, mathematical theory and computational algorithms so that we can synthesize and study more complex organizational structures. The solution of this class of basic research problems will have impact in structuring the distributed architectures necessary for the detection, discrimination, identification and classification of attributes of several targets (or events) by a collection of distinct sensors (or dispersed human observers).

The objective of the distributed organization will be the resolution of several possible hypotheses based on many uncertain measurements. Each hypothesis will be characterized by several attributes. Each attribute will have a different *degree of observability* to different decision makers or teams of decision makers; in this manner, we shall model different specialization expertise associated with the detection and resolution of different phenomena. Since each hypothesis will have several attributes, it follows that in order to reliably confirm or reject a particular hypothesis, two or more decision-makers (or two or more *teams* of decision-makers) will have to pool and fuze their knowledge.

Extensive and unecessary communication among the decision-makers will be discouraged by explicitly assigning costs to certain types of communication. In this manner, we shall seek to understand and isolate which communications are truly vital in the organizational performance; the very problem formulation will discourage communications whose impact upon performance is minimal. Quantitative tradeoffs will be sought.

We stress that we shall strive to design distributed organizational architectures in which teams of teams of decision-makers interact. For example, a team may consist of a *primary* decision-maker together with a *consulting* decision-maker -- the paradigm used by Papastavrou and Athans.

The methodology that we plan to employ will be mathematical in nature. To the extent possible we shall formulate the problems as mathematical optimization problems. Thus, we seek *normative solution concepts*. To the extent that human *bounded rationality* constraints are available, these will be incorporated in the mathematical problem formulation. In this case, the nature of the results will correspond to what is commonly refered to as *normative/descriptive* solutions. Therefore, we visualize a dual benefit of our basic research results. From a purely mathematical point of view, the research will yield nontrivial advances to the distributed hypothesis-testing problem; an very difficult problem from a mathematical point of view. From a psychological perspective, we hope that the normative results will suggest *counterintuitive* behavioral patterns of -- even perfectly rational -- decision-makers operating in a distributed tactical decision-making environment; these will set the stage for designing empirical studies and experiments and point to key variables that should be observed, recorded and analyzed by cognitive scientists. From a military C^3 viewpoint, the results will be useful in structuring distributed architectures for the surveillance/discrimination function.

Progress during the past quarter: In the past quarter we continued examining the problem of *ternary* hypothesis testing by a team of two cooperating decision makers; communication between the two decision-makers is costly and consists of a finite alphabet. The problem is to distinguish among three different hypotheses. Each decision-maker obtains an uncertain measurement of the true hypothesis. The so-called *primary* decision-maker has the option of making the final team decision or consulting, at a cost, the *consulting* decision-maker. The consulting decision-maker is constrained to provide information using a ternary alphabet. The team objective is to minimize the probability of error together with the communications cost (if any). This seemingly simple distributed decision problem turns out to have an extraordinarily complex structure. We have been able to quantify the nature of the optimal solution; we also were able to obtain a significant insight into the complexity of its solution. We obtained the necessary equations and are analyzing them.

Many more mathematical models and approaches remain to be developed. This research will most probably form the core of the Ph.D. research of J. Papastavrou under the supervision of Professor Athans.

A new student, Mr. Javid Pothiawala joined the project on September 1, 1987. He is now doing the necessary literature review in preparation for the selecting of a topic for his Master's thesis research.

We also studied and verified the analytical results reported by Noble at the ONR/DTDM contractor meeting.

Documentation: None as yet.

3.2 DISTRIBUTED HYPOTHESIS TESTING WITH MANY AGENTS

Background: The goal of this research project is to develop a better understanding of the nature of the optimal messages to be transmitted to a central command station (or fusion center) by a set of decision-makers (agents) who receive different information on their environment. In particular, we are interested in solutions of this problem which are tractable from the computational point of view. Progress in this direction has been made by studying the case of a large number of agents. Normative/prescriptive solutions are sought.

Problem Statement: Let H_0 and H_1 be two alternative hypotheses on the state of the environment

and let there be N agents (e.g. intelligent sensors) who possess some stochastic information related to the state of the environment. In particular, we assume that each agent i observes a random variable y_i with known conditional distribution $P(y_i|H_j)$, $j = 0, 1$, given either hypothesis. We assume that all agents have information of the same quality, that is, the random variables are identically distributed. Each agent transmits a binary message to a central fusion center, based on his information y_i. The fusion center then takes into account all messages it has received to declare hypothesis H_0 or H_1 true. The problem consists of determining the optimal strategies of the agents as far as their choice of message is concerned. This problem has been long recognized as a prototype problem in team decision theory: It is simple enough so that analysis may be feasible, but also rich enough to allow nontrivial insights into optimal team decision making under uncertainty.

Results: This being studied by Prof. John N. Tsitsiklis and a graduate student, Mr. George Polychronopoulos. Under the assumption that the random variables y_i are conditionally independent (given either hypothesis), it is known that each agent should choose his message based on a likelihood ratio test. Nevertheless, we have constructed examples which show that even though there is a perfect symmetry in the problem, it is optimal to have different agents use different thresholds in their likelihood ratio tests. This is an unfortunate situation, because it severely complicates the numerical solution of the problem (that is, the explicit computation of the decision threshold of each agent). Still, we have shown that in the limit, as the number of agents becomes large, it is asymptotically optimal to have each agent use the same threshold. Furthermore, there is a simple effective computational procedure for evaluating this single optimal threshold.

We have also shown that if each agent is to transmit K-valued, as opposed to binary messages, then still each agent should use the same decision rule, when the number of agents is large. Unfortunately, however, the computation of this particular decision rule becomes increasingly harder as K increases.

We have also investigated the case of M-ary ($M > 2$) hypothesis testing and constructed examples showing that it is better to have different agents use different decision rules, even in the limit as $N \to \infty$. Nevertheless, we have shown that the optimal set of decision rules is not completely arbitrary. In particular, it is optimal to partition the set of agents into at most $M(M-1)/2$ groups

and, for each group, each agent should use the same decision rule. The decision rule corresponding to each group and the proportion of the agents assigned to each group may be determined by solving a linear programming problem, at least in the case where the set of possible observations by each agent is finite.

In more recent work, the following have been accomplished.

(a) We studied the Neyman-Pearson (as opposed to Bayesian) version of the problem, in the case of M=2 hypothesis. The asymptotically optimal solution has been found and involves the Kullback-Liebler information distance.

(b) We considered a class of symmetic detection problems in which given any hypothesis H_i, each sensor has probability ε of making an observation indicating that some other hypothesis H_j is true. A simple numerical procedure has been found which completely solves this problem. Furthermore, a closed form formula for the optimal decision rules has been found for the case where the "noise intensity" ε is very small.

(c) For the above mentioned symmetric problem we have addressed and developed a methodology for solving the following question: is it better to have N processors sending a bits each, or is it better to have N/b processors sending a·b bits each? That is, for a given total communication rate, what is the best number of sensors?

We also conducted research which address the issue of the validity of asymptotic considerations when the number of agents N is moderate ($N \approx 5$).

Some of the above described results will appear in the Master's thesis of G. Polychronopoulos (expected January 1988) and will be reported in a journal paper.

Documentation

[1] J. N. Tsitsiklis, "On Threshold Rules in Decentralized Detection," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986; also LIDS-P-1570, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, June 1986.

[2] J. N. Tsitsiklis, "Decentralized Detection by a Large Number of Sensors," LIDS-P-1662, April 1987; to appear in *Mathematics of Control, Signals and Systems*.

3.3 COMMUNICATION REQUIREMENTS OF DIVISIONALIZED ORGANIZATIONS

Background: In typical organizations, the overall performance cannot be evaluated simply in terms of the performance of each subdivision, as there may be nontrivial coupling effects between distinct subdivisions. These couplings have to be taken explicitly into account; one way of doing so is to assign to the decisionmaker associated with the operation of each division a cost function which reflects the coupling of his own division with the remaining divisions. Still, there is some freedom in such a procedure: For any two divisions A and B it may be the responsibility of either decisionmaker A or decisionmaker B to ensure that the interaction does not deteriorate the performance of the organization. Of course, the decisionmaker in charge of those interactions needs to be informed about the actions of the other decisionmaker. This leads to the following problem. Given a divisionalized organization and an associated organizational cost function, assign cost functions to each division of the organization so that the following two goals are met: a) the costs due to the interaction between different divisions are fully accounted for by the subcosts of each division; b) the communication interface requirements between different divisions are small. In order to assess the communication requirements of a particular assignment of costs to divisions, we take the view that the decisionmakers may be modeled as boundedly rational individuals, that their decisionmaking process consists of a sequence of adjustments of their decisions in a direction of decreasing costs, while exchanging their tentative decisions with other decisionmakers who have an interest in those decisions. We then require that there are enough communications so that this iterative process converges to an organizationally optimal set of decisions.

Problem Statement: Consider an organization with N divisions and an associated cost function $J(x_1,...,x_N)$, where x_i is the set of decisions taken at the i-th division. Alternatively, x_i may be viewed as the mode of operation of the i-th division. The objective is to have the organization operating at a set of decisions $(x_1,...,x_N)$ which are globally optimal, in the sense that they minimize the organizational cost J. We associate with each division a decisionmaker DM_i, who is in charge of adjusting the decision variables x_i. We model the decisionmakers as "boundedly rational" individuals; mathematically, this is translated to the assumption that each decisionmaker will slowly and iteratively adjust his decisions in a direction which reduces the organizational costs. Furthermore, each decisionmaker does so based only on partial knowledge of the organizational cost, together with messages received from other decisionmakers.

Consider a partition $J(x_1,...,x_N) = \sum_{i=1}^{N} J^i(x_1,...,x_N)$ of the organizational cost. Each subcost J^i reflects the cost incurred to the i-th division and in principle should depend primarily on x_i and only on a few of the remaining x_j's. We then postulate that the decisionmakers adjust their decisions by means of the following process (algorithm):

(a) DM_i keeps a vector x with his estimates of the current decision x_k of the other decisionmakers; also a vector λ with estimates of $\lambda^k{}_i = \partial J^k/\partial x_i$, for $k \neq i$. (Notice that this partial derivative may be interpreted as DM_i's perception of how his decisions affect the costs incurred to the other divisions.

(b) Once in a while DMi updates his decision using the rule $x_i := x_i - \gamma \sum_{k=1}^{N} \lambda^k_i$, ($\gamma$ is a small positive scalar) which is just the usual gradient algorithm.

(c) Once in a while DM_i transmit his current decision to other decisionmakers.

(d) Other decisionmakers reply to DM_i, by sending an updated value of the partial derivative $\partial J^k/\partial x_i$.

It is not hard to see that for the above procedure to work it is not necessary that all DM's communicate to each other. In particular, if the subcost J_i depends only on x_i, for i, there would be no need for any communication whatsoever. The required communications are in fact determined by the sparsity structure of the Hessian matrix of the subcost functions J_i. Recall now that all that is given is the original cost function J; we therefore, have freedom in choosing the J_i's and we should be able to do this in a way that introduces minimal communication requirements; that is, we want to minimize the number of pairs of decisionmakers who need to communicate to each other.

Progress to Date: A graduate student, C. Lee, supervised Prof. J. Tsitsiklis, undertook the task of formulating the problem of finding partitions that minimize the number of pairs of DM's who need to communicate to each other, as the topic of his SM research. It was realized that with a naive formulation the optimal allocation of responsibilities, imposing minimal communication requirements, corresponds to the centralization of authority. Thus, in order to obtain more realistic and meaningful problems we did incorporate a constraint requiring that no agent should

be overloaded. A number of results have been obtained for a class of combinatorial problems, corresponding to the problem of optimal organizational design, under limited communications. In particular certain cases were solved; other cases have been successfully reformulated as linear network flow or assignment problems, for which efficient algorithms are known, and finally, somes cases were shown to be intractable combinatorial problems (NP-complete).

Documentation:

[1] C. Lee, "Task Allocation for Efficient Performance of a Decentralized Organization, LIDS-TH-1706, S.M. Thesis, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, September 1987.

These results were also overviewed at the annual ONR/DTDM contractor meeting, Newport, RI, September 1987.

3.4 COMMUNICATION COMPLEXITY OF DISTRIBUTED CONVEX OPTIMIZATION

Background: The objective of this research effort is to quantify the minimal amount of information that has to be exchanged in an organization, subject to the requirement that a certain goal is accomplished, such as the minimization of an organizational cost function. The problem becomes interesting and relevant under the assumption that no member of the organization "knows" the entire function being minimized, but rather each agent has knowledge of only a piece of the cost function. A normative/prescriptive solution is sought.

Problem Formulation: Let f and g be convex function of n variables. Suppose that each one of two agents (or decisionmakes) knows the function f (respectively g) , in the sense that he is able to compute instantly any quantities associated with this function. The two agents are to exchange a number of binary messages until they are able to determine a point x such that $f(g) + g(x)$ comes within ε of the minimum of f+g, where ε is some prespecified accuracy. The objective is to determine the minimum number of such messages that have to be exchanged, as a function of ε and to determine communication protocols which use no more messages than the minimum amount required.

Results: The problem is being studied by Professor John Tsitsiklis and a graduate student, Zhi-Quan Luo. We have shown that a least $0(n \log 1/\varepsilon)$ messages are needed and a suitable

approximate and distributed implementation of ellispsoid-type algorithms work with $0(n^2\log^2 1/\varepsilon)$ messages. The challenge is to close this gap. This has been accomplished for the case of one-dimensional problems (n=1), for which it has been shown that $0(\log 1/\varepsilon)$ messages are also sufficient. We have also generalized the technique employed in the one-dimensional case to obtain algorithms with only $0(n \log n \log 1/\varepsilon)$ messages which is within only $0(\log n)$ from the lower bound.

An interesting qualitative feature of the communication-optimal algorithms discovered thus far is the following: It is optimal to transmit aggregate information (the most significant bits of the gradient of the function optimized) in the beginning; then, as the optimum is approached more refined information should be transfered. This very intuitive result seems to correspond to realistic situtations in human decisionmaking.

Another problem which is currently being investigated concerns the case where are $K > 2$ decisionmakers cooperating for the minimization of $f_1 + ... + f_K$ where each f_i is again a convex function. This problem turns out to be very hard, but some progress has been made on a simpler version. Namely, we considered the problem of evaluating a simple function (say the sum of K numbers) by a hierarchy (tree) of decisionmakers and tight bounds have been obtained on the required amount of communication.

Documentation:

[1] J. N. Tsitsiklis and Z.-Q. Luo, "Communication Complexity of Convex Optimization," LIDS-P-1617, Laboratory for Information and Decision Systems, MIT,October 1986; *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December, 1986; This paper has been accepted for publication in the*Journal of Complexity*; also an invited talk was given at the *2nd Symposium on Complexity of Approximately Solved Problems*, Columbia University, New York, April 1987.

These results were also overviewed at the annual ONR/DTDM contractor meeting, Newport, RI, September 1987.

3.5 DISTRIBUTED ORGANIZATION DESIGN

Background: The bounded rationality of human decisionmakers and the complexities of the tasks they must perform mandate the formation of organizations. Organizational architectures distribute

the decisionmaking workload among the members: different architectures impose different individual loads and result in different organizational performance. Two measures of organizational performance are accuracy and timeliness. The first measure of performance addresses in part the quality of the organization's response. The second measure reflects the fact that in tactical decisionmaking *when* a response is generated is also significant: the ability of an organization to carry out tasks in a timely manner is a determinant factor of effectiveness.

The scope of work was divided into three tasks:

(a) Evaluation of Alternative Organizational Architectures;
(b) Asynchronous Protocols; and
(c) Information Support Structures.

During this year, the research effort has been organized around three foci. In the first one, we continue to work on the development of analytical and algorithmic tools for the analysis and design of organizations. In the second, we are integrating the results obtained thus far through the development of a workstation for the design and analysis of alternative organizational architectures. Finally, the experimental program, initiated last year with the objective of collecting data necessary to calibrate the models and evaluate different architectures for distributed decisionmaking, has been continuing and is expanding.

3.5.1 Design and Evaluation of Alternative Organizational Architectures.

In order to design an organization that meets some performance requirements, we need to be able to do the following:

(a) Articulate the requirements in qualitative and quantitative terms;
(b) Generate candidate architectures that meet some of the requirements;
(c) Evaluate the candidate organizations with respect to the remaining requirements;
(d) Modify the designs so as to improve the effectiveness of the organization;

The generalized Performance Workload locus has been used as the means for expressing both the requirements that the organization designer must meet and the performance characteristics of any specific design. Consider an organization with N decisionmakers. Then the Performance Workload space is an N+2 dimensional space in which two of the dimensions correspond to the

measures of the organization's performance (say, accuracy and timeliness) and the remaining N dimensions correspond to the measure of the workload of each individual decisionmaker. Two loci can be defined. First, the Requirements locus is the set of points in this N+2 dimensional space that satisfy the performance and workload requirements associated with the task to be performed by the organization. The second, the System locus, is the set of points that are achievable by a particular design. The design problem can then be conceptualized as the reshaping and repositioning of the System locus in the Performance Workload space so that the requirements are met.

Several thesis projects were continued during this period. The individual problem statements and a decription of the progress to date follow:

Generation of Flexible Organizational Structures

Problem Statement: Develop a methodology for modeling and analyzing classes of variable-structure organizations, i.e., organizations where the interactions between decision makers can change. This study is limited, however, to organizations in which their topology changes as a function of the tasks they perform. This constitutes another step towards the representation of more realistic human decisionmaking organizations.

The first objective is a precise definition of a variable-structure organization. Trade-offs exist indeed between the complexity of the mathematical description, the modeling power of the representation, and the limitations due to the computational implementation. The second objective is the explanation of results to be obtained from the comparison of the performance of organizations with variable structure and of the performance of organizations with fixed structure.

Progress to Date: This problem is being addressed by Jean-Marc Monguillet under the supervision of Dr. A. H. Levis. The focus of the research effort has been on the understanding of the meaning of the terms "architecture", "flexibility", "reconfigurability" and "variability", and on the identification of the appropriate mathematical tools for the description of variable architectures.

Since information processing occurs asynchronously and concurrently in these organizations, the Petri Net formalism is a convenient tool for modeling these systems. However, the Ordinary Petri Nets cannot take into account the changes in the connections between nodes. Their grammar

has to be extended.

The Colored Petri Net formalism seemed to be the appropriate extension to be used. It allows to color the different possible structures of the organization and the incoming tokens (i.e., the tasks) which correspond to them. This leads to the representation of the organization as layers of structures. The formalism also allows changes in colors and interconnections of the structures. Unfortunately, when the number of colors is too large, the representation becomes extremely complicated, and cannot be represented graphically. This reason has lead us to investigate the properties of nets of higher level, namely the Predicate-Transition Nets.

In Predicate-Transition Nets, the tokens, instead of being colored items following colored paths, are specific values of variables. They are the arguments of predicates associated with the places, and of logical formulas built in the transitions, which decide where the tokens will be directed in the firing process. These nets are therefore very appropriate for the treatment of organizational structures with changing properties and relations. Besides, the graphical representation they give is much clearer than in the other formalisms.

The modeling of a three member variable-structure organization carrying out an air defense task (AAW) with scarce weapon resources is being investigated. Each decisionmaker (DM) has his internal structure represented by the four-stage model. This allows to differentiate the kind of interactions that two different decisionmakers may have between them. Depending on the threat, which can be of several types, the interactions between DM's differ. This model is serving as the basis for the description of a methodology for the modeling of Variable Structure Decision Making Organization (VDMOs). This methodology consists of five steps, each of which addresses a different function:

(1) input-output: in this step, the interaction with the environment is modeled; the set of inputs is partitioned in classes which correspond to a specific pattern of interactions.

(2) shared resources: DM's are modeled as colored tokens constituting the initial marking of a shared resource, i.e., *the DM's are considred as another resource of the organization.*

(3) possible interactions: the topologies of the interactions are represented, regardless of which DMs are assigned to the various functions.

(4) switching module: this is the interface between the classes of incoming signals, the DM's who will be involved in their processing, and the interactions which will be selected.

(5) labeling: description of the algorithms that the transitions represent in the net.

Several examples of such a methodology have been developed including the three member organization carrying out the air defense task, a two member organization where each DM is alternatively Headquarters or a Field Unit, and a two member organization with variable interactions with a decision support system.

The research effort is now focused on the computation of performance measures of a VDMO modeled with Predicate Transition nets as opposed to the performance measures of comparable fixed structure DMO's. The objective is to obtain the system loci of the VDMO and of the FDMO's from which the VDMO is derived, as to compare their respective measures of effectiveness.

Documentation: None yet.

Design of Organizations

Objective: Given a feasible organizational architecture, develop a methodology for (a) identifying the functions that must be performed by the organization in order that the task be accomplished, (b) selecting the resources (human, hardware, software) that are required to implement these functions, and (c) integrating these resources - through interactions - so that the system operates effectively.

Progress to Date: This research problem is being investigated by Stamos K. Andreadakis under the supervision of Dr. A. H. Levis. The design methodology has been modified in order to address the following formulation of the design problem of decision making organizations: Given a mission, design the DM organization that is accurate, timely, exhibits a task processing rate that is higher than the task arrival rate, and whose decisionmakers are not overloaded. The design requirements explicitly stated are:

The accuracy J must be greater than a threshold J_0 or, equivalently, that the expected cost J be

less than the threshold J_0:

$$J < J_0 \qquad [1]$$

The timeliness measure T be less than a threshold T_0:

$$T < T_0 \qquad [2]$$

The task processing rate R be greater than the task arrival rate R_0:

$$R > R_0 \qquad [3]$$

The constraints that must be observed are: each decisionmaker must not be overloaded, i.e., the decisionmakers' information processing rate F be less than the rationality threshold F_0:

$$F < F_0 \qquad [4]$$

Design methodology:

The design methodology has four phases: in phase 1 a data flow structure generator produces a set of candidate data flow structure designs, from which a few representative data flow structures are selected. In phase 2 the activity of the functions, the accuracy, the processing time and the processing rate of each data flow structure are computed. In phase 3, each data flow structure is augmented and transformed into a C^2 organization. The functions are allocated to decisionmakers and the communication protocols are designed. In phase 4 the evaluation of the measures of performance of each C^2 organiztion is performed and then the respective measures of effectiveness are computed.

The designs are modified to increase the measure of effectiveness by introducing decision aids, changing the function allocation, or modifying the protocols. The introduction of the hardware, i.e., the specifications for the required decision aids and databases as well as for the communications links (the command and control systems) transforms each decision-making organization into the corresponding command and control organization.

Finally a command and control organization is selected from the candidate designs on the basis of

the greatest MOE value.

Application of the Design Methodology to Battle Group Air Defense

A naval anti-air-warfare example is employed to illustrate the synthesis methodology. The objective is to design a Command and Control organization for the outer air battle.

The synthesis of a C^2 organizations involves the following steps:

- Develop a simple model of the outer air battle
- Identify the decision-making functions and the corresponding algorithms
- Develop suitable data flow structures
- Develop software for the computation of workload
- Compute measures of performance (accuracy, response time, processing rate)
- Compute the measure of effectiveness for each candidate organization
- Compare the organizations on the basis of the MOE value.

During the past quarter, a model of outer air battle has been developed. While simple, the model preserves the following important features:

(1) Threat identification (classification) on the basis of emmitter signature and threat velocity.
(2) Development of courses of action considering the strength of the incomming raid and the type of enemy aircraft. Due to limited information about naval air tacticts, the development of courses of action is in essence a mapping from the situation assessment to a set of courses of action, which are identified by labels and are context free (black box approach).
(3) Response selection from the available courses of action based on the availability of resources.

Data flow structures have been developed and the input alphabet (set of input cases) has been defined. Two of the candidate data flow structures have been selected to be transformed into C^2 organizations, and will be studied in detail.

Software is currently being developed to compute the workload imposed by the processing functions of the decisionmaker, and the accuracy of the C^2 organizations.

The computation of the probability density functions of response time and processing rate will be performed by a new version of the software developed to compute the effect of jamming on the pdf of response time.

Documentation:

[1] A. H. Levis and S.K. Andreadakis, "Computer-Aided Analysis of Organizations," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986.

[2] S.K. Andreadakis and A. H. Levis, "Accuracy and Timeliness in Decision-Making Organizations," *Proc. 10th IFAC World Congress*, July 27-31, 1987, Munich, FRG and *Proc. 9th MIT/ONR Workshop on C^3 Systems*, LIDS-R-1624, MIT Cambridge, MA, December 1986.

[3] S. K. Andreadakis and A. H. Levis, "Design Methodology for Decision-Making Organizations," *Proc. of C^3 Symposium*, June 1987, Washington DC.

Performance Evaluation of Organizations with Decision Aids

Problem Statement: Analyze and evaluate the impact of decision aids, i.e., preprocessors and decision support systems, on the effectiveness of decisionmaking and information processing organizations. In particular, investigate the concept of coordination of decisionmakers assisted by those decision aids.

Progress to Date: This work is being done by Jean-Louis Grevet under the supervision of Dr. A.H. Levis. From a conceptual standpoint, the idea of coordination in decision-making organizations embodies three classes of issues:

- the extent to which the decisionmakers constitute a team.
- the synchronization of the decisionmakers' activities during the decisionmaking process.
- the consistency of the information processed by the different members of the organization.

The latter class of issues is primarily related to the fact that decisionmakers do not necessarily

process data that are consistent because they have different geographical or temporal origins : For instance, two different decisionmakers can process data originating from different sensors or different databases as well as data originating from a common database but accessed at different instants.

The work currently done is focused more specifically on the first two classes of issues mentioned above.

(a) The concept of team of decision-makers has been clarified. A team of decisionmakers is defined as being an organization in which the members :
- have a common goal
- have the same interests and same beliefs
- have activities which must be coordinated so that they achieve a higher performance.

Thus, for a task X with probability distribution p(X) and a cost function c(X) for the organization, one condition for the organization to be a team is that its members have the same perception of the task $p_T(X)$, i.e. the same beliefs about the task, and assign the same cost $c_T(X)$ to each input, i.e have the same interests as far as the task is concerned.

The team will account perfectly for the organizational objectives when:

$$p_T(X) = p(X) \text{ and } c_T(X) = c(X)$$

(b) The issue of synchronization is related to the interactions between the decisionmakers that take place during the decisionmaking process. It is thus a dynamic characteristic of the organization. When a decisionmaker DM_i processes some information, the total processing time of this input for DM_i consists of two distinct parts:
- the time T_p during which the decisionmaker actually processes the information
- the time T_m spent by the information in the memory of the decisionmaker without being processed.

The time T_m is the result of two factors:

- information can remain in the memory of the decisionmaker until he decides to process it

using the relevant algorithm. In this case, the decisionmaker processes several pieces of information at the same time. Since a particular algorithm cannot process two inputs at the same time, some inputs will have to remain unprocessed in memory waiting until he relevant algorithm is free.

- Information can also stay in memory because the decisionmaker waits to receive a necessary piece of information from another decisionmaker or a decision support system.

An organization is not well synchronized when the decisionmakers have to wait for long periods of time before receiving the information that they need in order to continue their processing. On the contrary, the organization is well synchronized when those lags are small. This is an important concept because the processing of information introduces two kinds of biases:

- biases due to the uncertainty embodied in the information processed and to the models used.
- biases due to the value of the information for the decisionmaker when he actually processes it. Thus, if a piece of information remains for a long time in memory, the decisionmaker might well attach less value to it when he actually processes it. This could lead to a degradation of the effectiveness of the organization.

However, perfect synchronization of the organization does not imply necessarily that the delay for the processing of one input will be low. Two decisionmakers can be perfectly synchronized but very slow; they can also be not perfectly synchronized but very fast. In the same way, good synchronization does not ensure that the organizational response will be perfectly accurate: Indeed, in order to be well synchronized one DM might use algorithms which introduce important biases in his response because he wants to be faster in order to keep up with the other DM; a DM can also take more time to do his processing in order to provide better responses but, then, either his message might be of no value to the other DM because it arrived too late or the organizational response might not be timely. Thus, we can see that synchronization has important ramifications; its relationship to the effectiveness of the organization must be investigated.

A measure of performance S based on this concept has been defined with the use of Timed Petri-Nets.

The impact of decision aids will be assessed from the following two standpoints:

(1) the extent to which a preprocessor can coordinate the strategies of the decisionmakers and

increase their cohesiveness as a team.

(2) the impact of decision support systems on the overall decision-making process.

A generic model of a decision-maker assisted by a decision support system has been proposed. It accounts for the fact that most real systems contain both elements of centralization and decentralization, i.e., the users can share certain resources - centralized databases on mainframes - and access individually other facilities such as intelligent terminals. This modifies the strategy of each decision-maker, who now must integrate in his choices the possibility of requesting information from the DSS. Thus, each decision-maker has three alternatives vis-à-vis the DSS:

- he can ignore it and process the information by himself.
- he can query it and rely totally on the response.
- he can query it and compare the response to his own perception of the issue.

These choices are consistent with the analysis carried out by Scott Weingaertner for the submarine ship control party and reported earlier. The evaluation will be carried out on an example , a two-person hierarchical organization. The tools used to carry out this analysis are of two types:

- a simulation program of Petri-nets on the MacIntosh using the Design Open Architecture Development System of MetaSoftware Corp. has been developed. It will be used to get insight in the dynamic performance of the organization under different configurations, i.e., basic organization, organization with preprocessor, and organization with preprocessor and DSS.
- the computation of three measures of performance, accuracy J, expected delay T, and synchronization S will be done for the steady-state behavior of the organization under the same configurations. The performance loci of the organization will then be plotted using the CAESAR software.

The expected results are that a preprocessor can help to coordinate to a certain extent the activities of different decision-makers, but that the introduction of a decision support system can lead to mixed results depending on the coordination of the decisionmakers with respect to the use of the DSS and on the configuration of the DSS.

Documentation: No formal documentation yet. A thesis is being written to report on this research task.

3.5.2 Computer Aided Evaluation of System Architectures

During the six-month period March to September 1987, the research effort focused on the integration of the computational and graphical tools to be used in the design of organizations, i.e., the development of CAESAR (Computer-Aided Evaluation of System Architectures). CAESAR consists of four major components:

The **Architecture Generator** which constructs feasible organizational forms using Petri Nets formalism.

The **Analysis and Evaluation Module** which contains algorithms for the analysis of organizational archictectures and the computation of the Measures of Performance.

A **Data Base** which is used to store the results of the analysis.

The **Locus** module which contains routines that construct the Performance Workload locus of an organization form that is carrying out a given task, as well as routines that compute a present graphically selected measures of effectiveness (MOEs).

The structure of the software system is shown in Figure 1. CAESAR incorporates theoretical and computational developments obtained over a period of seven years through more than ten theses. Some modules are being developed explicitly under this contract; others are being developed with support by the Joint Directors of Laboratories.

ARCHITECTURE GENERATOR

DMO Gen.AT. Program that generates the Petri Nets of Decisionmaking Organizations that satisfy a set of structural constraints, as well as constraints imposed by the user. The algorithm is based on P. Remy's thesis (1986) and has been implemented in DOS 3.0 © IBM, using Turbo Pascal 3.01A ©Borland International and Screen Sculptor ©Software Bottling Company. **Status:** Program operational (6/87).

DMO Des.AT. Interactive graphics program for the construction of the Petri Nets of arbitrary organizational architectures. It can be used to create and store subsytsems and to combine them to form large organizational structures. Program, developed by I. Kyratzoglou, also creates the analytical description of the Petri Nets. Implemented in DOS 3.0, Professional Fortran, Graphics Tool Kit, and Graphic Kernel System, all ©IBM. **Status:** Program Operational (8/87).

DMO Des.Mac. Interactive graphics program for the construction of the Petri Nets of arbitrary

organizations. It can be used to design organizations of arbitrary size through the use of nested subnets. Program developed for the Apple Macintosh using the Design Open Architecture System ©Meta Software Corp. The program creates the analytical description of the Petri Net, as well as store functions and attributes represented by the transitions, places, and connectors. Program continues to be enhanced by J. L. Grevet and L. Jandura to be consistent with analytical description of Petri Nets used in various algorithms. **Status:** Program operational.

MacLink ©Dataviz. Commercial software for converting and transmitting files between the DOS machines and the Macintosh. **Status:** MacLink has been installed and is operational.

Incidence Matrix / Attributes. Standard form for the data structure of Petri Nets. The files contain the incidence matrix or flow matrix of the Petri Net and the attributes and functions associated with the elements of the net.**Status:** Standard version of incidence matrix has been implemented. Operational (7/87).

ANALYSIS AND EVALUATION MODULE

Matrix Conversion. Simple algorithm that transforms the incidence matrix into the interconnection matrix used in Jin's algorithm. Algorithm in Turbo Pascal 3.01A. **Status:** Algorithm is operational.

Paths. Algorithm developed by Jin in her thesis that determines all the simple paths and then constructs the concurrent paths in an organizational architecture. This is an efficient algorithm that obtains the answers by scanning the interconnection matrix. Algorithm in Turbo Pascal 3.01A. **Status:** Program is operational.

Delay. Simple algorithm that calculates path delays and expected delay when processing delays are constant. Algorithm in Turbo Pascal 3.01A. **Status:** Algorithm is operational.

Del Com. Algorithm developed by Andreadakis that calculates measures of timeliness when the processing delays are described by beta distributions. It also accounts for the presence of jamming and its effect on timeliness. Algorithm in Turbo Pascal 3.01A. **Status:** Problem specific version operational.

Res Con. Algorithm developed by Hillion in his thesis that calculates the maximun throughput in a Timed Event Graph, a special class of Petri Nets. It also detrmines the optimal schedule in the presence of resource and time constraints. The procedure incorporates an algorithm proposed by Martinez and Silva for determining simple paths through the calculation of s-invariants. A second version, based on the algorithm by Alaiwan and Toudic, is also included. **Status:** Independent version of algorithm is operational; integrated version in workstation is also operational (6/87).

PW Comp 3. Algorithm for the computation of a three-person organization's performance measure J (Accuracy) and the workload of each one of the decisionmakers. The algorithm computes the accuracy of the response and the workload for each admissible decision strategy. This version was developed by Andreadakis in Turbo Pascal. **Status:** Program is operational.

PW Comp 5. A variant of PW Comp 3, but for a five-person organization modeling the ship control party of a submarine. Algorithm developed by Weingaertner as part of his thesis. Implemented in Turbo Pascal. **Status:** Program is operational (1/87).

DATA BASE MODULE

LOCUS Data File. Data file in which the results from the evaluation of a decisionmaking organization (i.e., the MOPs) are stored. The file, as currently structured, can accommodate seven measures of performance - accuracy, timeliness, and workload for five persons. It also contains four indices that specify the decision strategy associated with each record. Development of a general structure that can hold an arbitrary number of MOPs is limited by the memory constraints of the IBP PC/AT. The same data structure is used to store data files used in the determination of measures of effectiveness. **Status:** The seven MOP version is operational.

LOCUS MODULE

LOCUS. Graphics plotting program that generates two or three dimensional loci or two- and three-dimensional projections of higher dimensional loci. This is the basic program used to construct the Performance - Workload locus of an organization. Basic version developed by Andreadakis and Bohner and described in latter's thesis (1986). **Status:** Version using professional graphics controller is operational. Revised transportable version adhering to the VDI standard and with improved user interface is also operational. This version can handle up to five Decisionmakers.

ISO Data. Algorithm for obtaining some measures of effectiveness from the measures of performance stored in the Locus Data file. Specifically, it finds isoquants: e. g., locus of constant accuracy, or constant workload. **Status:** New VDI version for microcomputers being implemented by Azzola on the basis of a design by Weingaertner is operational.

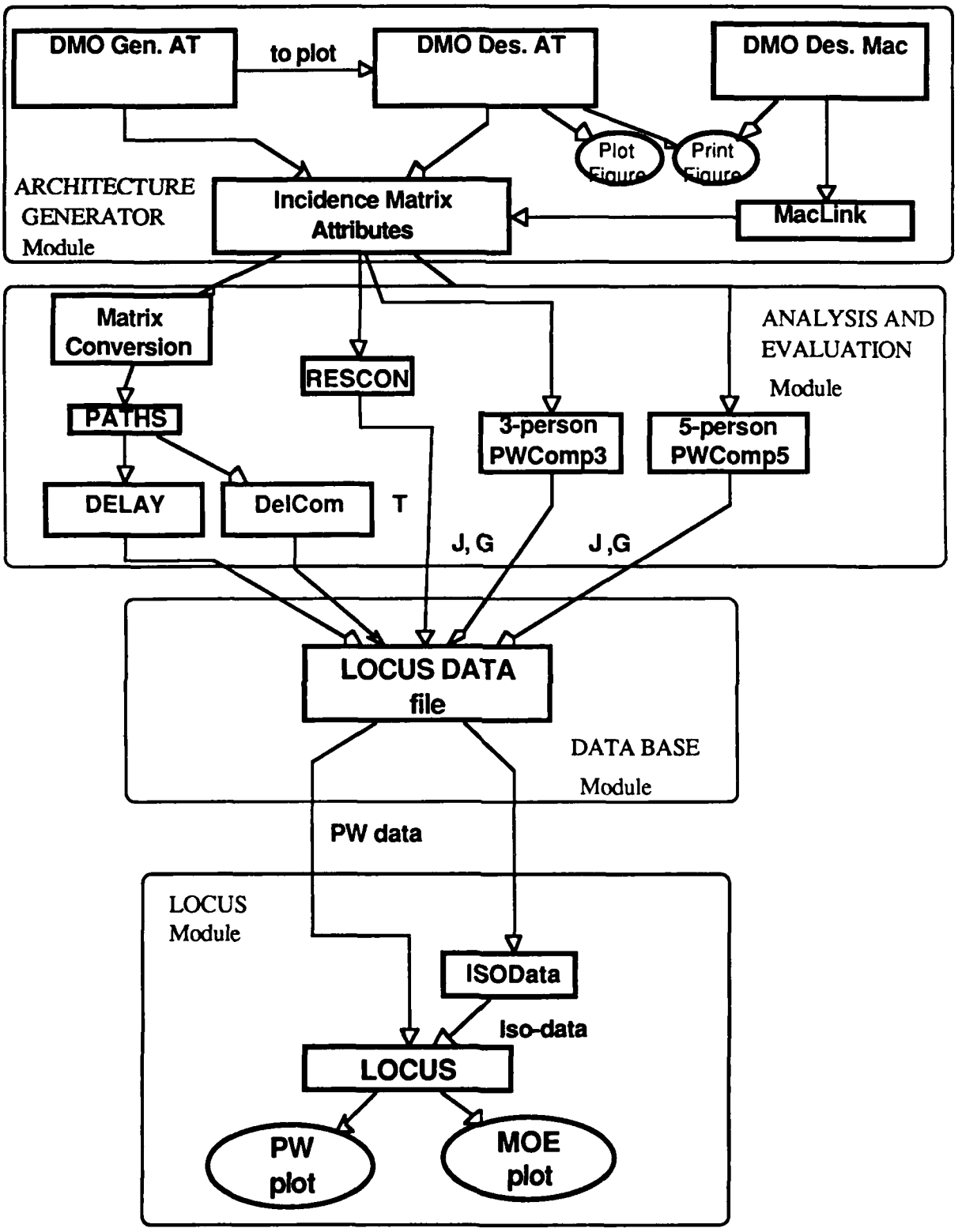
INPUT / OUTPUT

Output. By adopting the Virtual Device Interface (VDI) standard and the Enhanced Graphics standard, it became possible to develop a version of the CAESAR software that is transportable to other IBM PC ATs or compatibles and to drive a wide variety of output devices. The VDI version is now operational and can drive various monitors, printers, and plotters.

Input. A uniform user interface with windowing capability is needed to make the system useable by analysts and designers. Commercially available software are being investigated to select the most appropriate one. In the meantime, a workable user interface has been developed.

The effort in the following months will be focused on investigating further the modules shown in Figure 2 and begin the integration of the remaining modules shown in Figure 1. More modules will be added as new research results are obtained.

The version of Figure 2 was demonstrated at the Annual review of the DTDM Program at the Naval War College, Newport, RI.



CAESAR: Computer - Aided Evaluation of System ARchitectures v. 1.0. 3/87

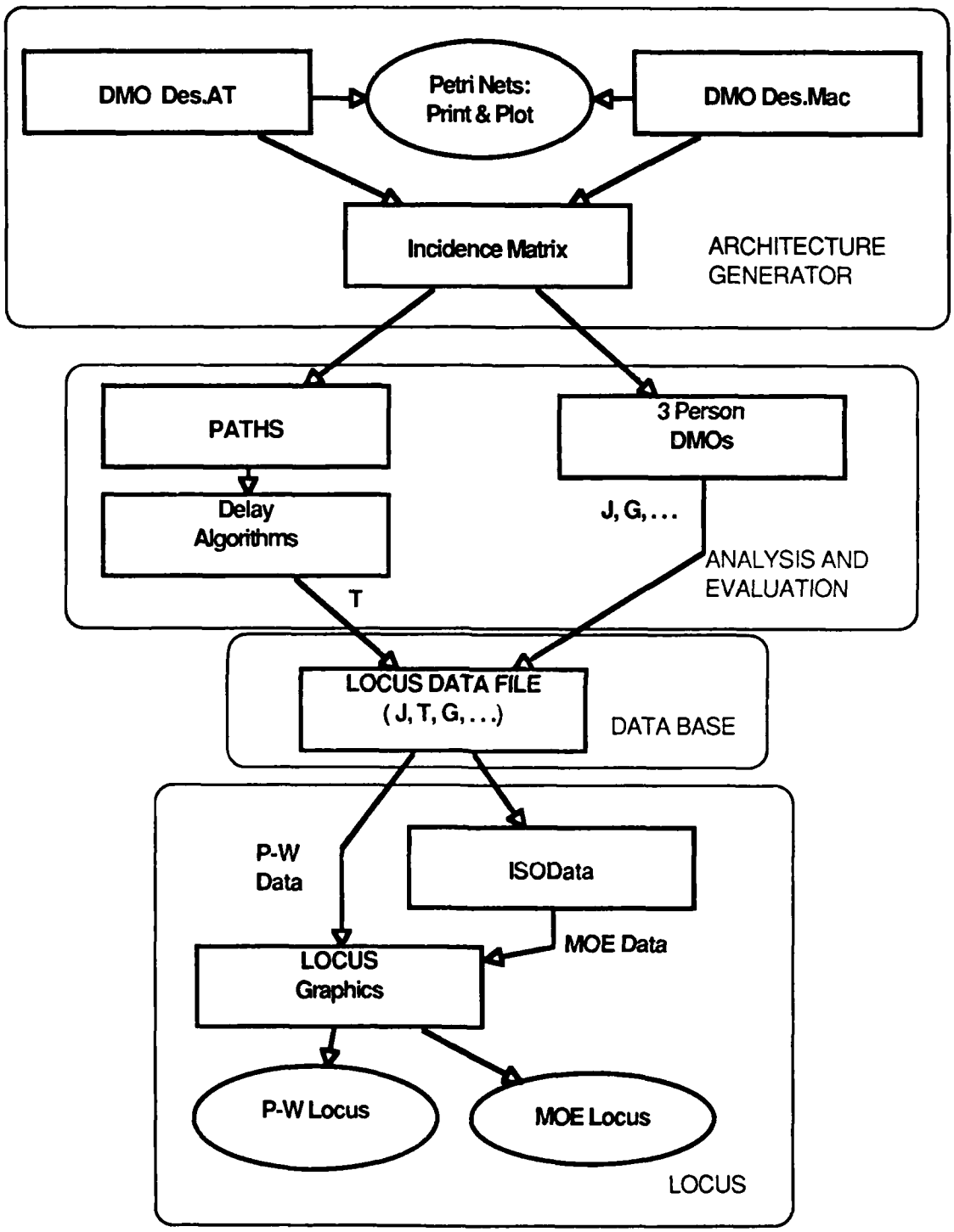


Fig. 2 CAESAR 9/87

3.5.3 Design of Experiments

A major application of CAESAR is in the design and analysis of experiments in which different organizational forms will be evaluated. At this time two related projects are underway. In the first one the applicability of certain methodologies in the physical sciences for the design of experiments to the behavioral sciences is being explored. In the second one, CAESAR is used to evaluate the model of the experiment that has been carried out to determine the stability of the bounded rationality constraint.

3.5.3.1 Experimental Design Using Dimensional Analysis

One of the difficulties in designing multi-person experiments is the large number of parameters that can be varied. A rigorous procedure is needed that will allow us to choose with parsimony which experimental parameters to keep constant and which to vary. Dimensional analysis is such a procedure that has had extensive application in the physical sciences, both in experimental and theoretical work.

The methods of dimensional analysis* are based on the principle of dimensional homogeneity, i.e., all relations describing a system behavior must be dimensionally consistent. When the relations governing a process are unknown or too complex, dimensional analysis can be used to design an experimental program by reducing the number of variables that need to be varied and by suggesting possible hypotheses (relations between variables) that can be investigated. The theoretical foundation of the approach used in this task is Buckingham's Pi Theorem.

If there are N physical quantities of importance and m fundamental dimensions, then there exists a maximum number (N_{max}) of these quantities which in themselves cannot form a dimensionless group, where $N_{max} \leq m$. We then use the N_{max} quantities, called primary ones, to construct n dimensionless group π, where $n = N\ N_{max}$. In most cases, we choose N_{max} to be equal to m. The procedure consists of three steps.

*Description of dimensional analysis adapted from "Heat, Mass, andMomentum Transfer" by W.M. Rohsenow and H. Choi, Prentice Hall, 1961.

(1) Compile a tentative list of all significant variables for the phenomenon of interest. The relationship between these N variables can be expressed symbolically as

$$f(Q_1, Q_2,...,Q_N) = 0$$

where the Q's represent the variables. Let m be the number of fundamental dimensions, such as time, length, information, number of objects, etc.

(2) Now select N_{max} quantities which by themselves cannot form a dimensionless group. There is no unique set, but a good choice is to select a set of Q's so that each contains one of the fundamental dimensions at least once.

(3) Form each π term by expressing it as the ratio of the remaining Q's to the product of powers of the primary Q's. The original symbolic equation can be replaced with

$$\phi(\pi_1, \pi_2,...,\pi_N)$$

where $n = N\text{-}N_{max}$.

This method is being applied to the experiment designed by J. Casey and A. C. Louvet for two reasons - to test the applicability of the procedure to experiments involving cognitive processing, and to verify independently the inferences made from the statistical analysis of the experimental results.

This project has been undertaken by V. Jin under the supervision of Dr. A. H. Levis. As a first step, three dimensions are being considered: time (T) measured in seconds, information (I) measured in bits, Tasks (S) measured in symbols. The relationship f is selected as the performance index J expressed as a function of the other variables

$$J = f(Q_1, Q_2,...,Q_{N-1}).$$

This is consistent with the experiment which measured performance as a function of the time per task for two experimental conditions. The results of the analysis will be presented in the next

report.

3.5.3.2 Experimental Evaluation of the Output of Overload

The first part of the research consisted of designing and running an experiment which would explore some of the problems concerning performance of human decsisonmakers under time constraints. It was shown that there is a maximum rate of information processing under which subjects can operate. The results also showed that the bounded rationality constraint is stable when the framing of the task is slightly modified, and that it is normally distributed over the subjects. The results were documented in a paper presented at the 1987 Symposium on C^3 Research.

The next step of the research has been to quantify the bounded rationality constraint using both the results from the experiment and Information Theory.

Algorithms and Workload

After running the experiment, subjects were asked to describe the algorithm(s) that they had used to perform the task. Simple mathematical models which took into account the algorithms described by the subjects have been developed.

First attempts to compute the workload surrogate associated with the mathematical models have been made. Because of the very large input alphabet and of the restrictions which had been made on the ratios of each trials, the computation of the workload can not be made without approximations. The workload which will eventually be computed, will represent the average workload for a task of four or seven trials but not the exact workload. Work is continuing to develop the computational procedures for estimating the workload surrogate for the tasks un the experiment.

This work is being carried out by A.-C. Louvet under the supervision of Dr. A. H. Levis.

Documentation:

[1] A. C. Louvet, J. T. Casey, A. H. Levis, "Experimental Investigation of the Bounded Rationality Constraint" *Proc. of C^3 Symposium*, June 1987, Washington, DC.

5. RESEARCH PERSONNEL

Prof. Michael Athans,	Co-principal investigator
Dr. Alexander H. Levis,	Co-principal investigator
Prof. John Tsitsiklis,	
Mr. Stamatios Andreadakis	graduate research assistant (Ph.D)
Ms. Victoria Jin	graduate research assistant (Ph.D)
Mr. Jason Papastavrou	graduate research assistant (Ph.D)
Mr. Jean-Louis Grevet	graduate research assistant (M.S.)
Mr. Jean-Marc Monguillet	graduate research assistant (M.S.)
Ms. Anne-Claire Louvet	graduate research assistant (M.S.)
Mr. Javid Pothiawala	graduate research assistant (M.S.)

6. DOCUMENTATION

6.1 Theses

[1] J. N. Tsitsiklis, "Problems in Decentralized Decisionmaking and Computation," Ph.D. Thesis, Dept. of EECS also, Report LIDS-TH-1424, Laboratory for Information and Decision Systems, MIT, December 1984.

[2] G. J. Bejjani, "Information Storage and Access in Decisionmaking Organizations," MS Thesis, Technology and Policy Program, also, Report LIDS-TH-1434, Laboratory for Information and Decision Systems, MIT, January 1985.

[3] Y. V.-Y. Jin, "Delays for Distributed Decisionmaking Organizations," MS Thesis, Mechanical Engineering, also, Report LIDS-TH-1459, Laboratory for Information and Decision Systems, MIT, May 1985.

[4] K. L. Boettcher, "A Methodology for the Analysis and Design of Human Information Processing Organizations," Ph.D., Thesis, Dept. of Electrical Engineering and Computer Sciences, also, Report LIDS-TH-1501, Laboratory for Information and Decision Systems, MIT, September 1985.

[5] R. P. Wiley, "Performance Analysis of Stochastic Timed Petri Nets," Ph.D. Thesis, Dept. of Electrical Engineering and Computer Sciences, also, Report LIDS-TH-1525, Laboratory for Information and Decision Systems, MIT, January 1986.

[6] J. D. Papastavrou, "Distributed Detection with Selective Communications," MS Thesis, Dept. of Electrical Engineering and Computer Sciences, also, Report LIDS-TH-1563, Laboratory for Information and Decision Systems, MIT, May 1986.

[7] C.M. Bohner, "Computer Graphics for Systems Effectiveness Analysis," MS Thesis, Technology and Policy Program, also, Report LIDS-TH-1573, Laboratory for Information and Decision Systems, MIT, June 1986.

[8] H. P. Hillion, "Performance Evaluation of Decisionmaking Organizations Using Timed Petri Nets," MS Thesis, Technology and Policy Program, also, Report LIDS-TH-1590, MIT, August 1986.

[9] P. A. Remy, "On the Generation of Organizational Architectures Using Petri Nets," MS Thesis, Technology and Policy Program, also, Report LIDS-TH-1630, Laboratory for Information and Decision Systems, MIT, December 1986.

[10] C. Lee, "Task Allocation for Efficient Performance of a Decentralized Organization," MS, Thesis, Dept of EECS, also, Report LIDS-TH-1706, Laboratory for Information and Decision Systems, MIT, September 1987.

6.2 Technical Papers

[1] R. P. Wiley and R. R. Tenney, "Performance Evaluation of Stochastic Timed Decision-Free Petri Nets," *Proc. 24th IEEE Conference on Decision and Control*, December 11-13, 1985, Ft. Lauderdale, FL, pp. 558-563.

[2] G. J. Bejjani and A. H. Levis, "Information Storage and Access in Decisionmaking Organizations," LIDS-P-1466, Laboratory for Information and Decision Systems, MIT, May 1986.

[3] J. N. Tsitsiklis and M. Athans, "On the Complexity of Decentralized Decisionmaking and Detection Problems, *IEEE Trans. on Automatic Control*, Vol. AC-30, No. 5, May 1985.

[4] V. Y.-Y. Jin and A. H. Levis, "Computation of Delays in Acyclical Distributed Decisionmaking Organizations," LIDS-P-1488, Laboratory for Information and Decision Systems, MIT, August 1985.

[5] K. L. Boettcher, and R. R. Tenney, "A Case Study in Human Team Decisionmaking," Proc. Systems, Man, and Cybernetics, Tucson, AZ, November 1985.

[6] K. L. Boettcher and R. R. Tenney, "On the Analysis and Design of Human Information Processing Organizations," LIDS-P-1503, *Proc. 8th MIT/ONR Workshop on C^3 Systems*, December 1985.

[7] K. L. Boettcher and R. R. Tenney, "Distributed Decisionmaking with Constrained Decisionmakers - A Case Study," *Proc. 8th MIT/ONR Workshop on C^3 Systems*, December 1985, also in *IEEE Trans. on Systems, Man, and Cybernetics*, Vol. SMC-16, No. 6, November/December 1986.

[8] R. P. Wiley and R. R. Tenney, "Calculating TImed-Related Performance Measures of a Distributed Tactical Decisionmaking Organization Using Stochastic Timed Petri Nets, *Proc. 8th MIT/ONR Workshop on C^3 Systems*, December 1985.

[9] V. Y.-Y. Jin, A. H. Levis, and P. A. Remy, "Delays in Acyclical Distributed Decisionmaking Organziations," LIDS-P-1528, Laboratory for Information and Decision Systems, MIT, Cambridge, MA, also in *Proc. 4th IFAC/IFORS Symposium on Large Scale Systems: Theory and Applications*, Zurich, Switzerland, August 1986.

[10] J. Papastravrou and M. Athans, "A Distributed Hypotheses-Testing Team Decision Problem with Communications Cost," LIDS-P-1538, Laboratory for Information and Decision Systems, MIT, February 1986, also in *Proc. 25th IEEE Conference on Decision and Control,* Athens, Greece, December 1986.

[11] J. Tsitsiklis, "On Optimal Thresholds in Decentralized Detection," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986.

[12] A. H. Levis and S. K. Andreadakis, "Computer-Aided Design of Organizations," *Proc. 25th IEEE Conference on Decision and Control*, Athens, Greece, December 1986.

[13] P. Remy , A. H. Levis, V. Jin, "On the Design of Distributed Organizational Structures," LIDS-P-1581, Laboratory for Information and Decision Systems, MIT, July 1986, *Proc. 10th IFAC World Congress*, Munich, FRG, July 1987.

[14] M. Athans, "Command-and-Control (C^2) Theory: A Challenge to Control Science," *IEEE Trans. on Automatic Control*, Vol. AC-32, No. 4, April 1987, pp. 286-293.

[15] P.A. Remy and A. H. Levis, "On the Generation of Organizational Architectures Using Petri Nets," Proc. Eighth European Workshop on Applications and Theory of Petri Nets, Zaragoza, Spain, June 24-26, 1987.

[16] H.P. Hillion and A.H. Levis, "Timed Event-Graph and Performance Evaluation of Systems, *Proc. Eighth European Workshop on Applications and Theory of Petri Nets*, Zaragoza, Spain, June 24-26, 1987.

[17] J. N. Tsitsiklis, D.P. Bertsekas, and M. Athans, "Distributed Asynchronous Deterministic and Stochastic Gradient Optimization Algorithms," *IEEE Trans. on Automatic Control*, Vol. AC-31, No. 9, September 1986.

[18] S. K. Andreadakis and A. H. Levis, "Design Methodology for Decision-Making Organizations," *Proc. 1987 C^3 Symposium*, National Defense University , Fort McNair, Washington DC, June 1987.

[19] A. C. Louvet, J. T. Casey, A. H. Levis, "Experimental Investigation of the Bounded Rationality Constraint," *Proc. 1987 C^3 Symposium*, National Defense University , Fort McNair, Washington DC, June 1987.

[20] H. P. Hillion and A. H. Levis, "Performance Evaluation of Decisionmaking Organziations," *Proc. 1987 C^3 Symposium*, National Defense University , Fort McNair, Washington DC, June 1987.

[21] S. T. Weingaertner and A. H. Levis, "Evaluation of Decision Aiding in Submarine Emergency Decisionmaking," *Proc. 1987 C^3 Symposium*, National Defense University , Fort McNair, Washington DC, June 1987.

[22] P. J. F. Martin and A. H. Levis, "Measures of Effectiveness and C^3 Testbed Experiments," *Proc. 1987 C^3 Symposium*, National Defense University , Fort McNair, Washington DC, June 1987.

[23] P. A. Remy and A. H. Levis, "On the Genration of Organizational Architectures Using Petri Nets," *Proc. Eighth European Workshop on Applications and Theory of Petri Nets*, Zaragoza, Spain, June 24-26, 1987.

[24] H. P. Hillion and A. H. Levis, "Timed Event-Graph and Performance Evaluation of Systems," *Proc. Eighth European Workshop on Applications and Theory of Petri Nets*, Zaragoza, Spain, June 24-26, 1987.

[21] J. Papastavrou and M. Athans, "A Distributed Hypothesis-Testing Team Decision Problem with Communications Cost," in *S.Tzafestas et al. (eds.), System Fault Diagnostics, Reliability and Related Knowledge-Based Approaches,"* Volume 1, pp. 99-130, 1987, D. Reidel Publishing Company.

[22] J. N. Tsitsiklis and Z.-Q. Lee, "Communication Complexity of Convex Optimization," *Journal of Complexity*, September 1987.

[23] P.A. Remy, A. H. Levis, and V. Y.-Y. Jin, "On the Design of Distributed Organizational Structures," *Automatica*, (in press).

END

FILMED

FEB. 1988

DTIC